

Acoustic VTI wavefield tomography of P-wave surface and VSP data

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Seismic tomography methods

	Ray-based	Wave-based
Data domain	Traveltime tomography	Full-waveform Inversion
Image domain	Ray-based MVA	Wave-equation MVA

P-wave kinematics in VTI media

- ▶ velocity

$$V_{P0}, \epsilon, \delta \text{ or } V_{\text{nmo}}, \eta, \delta$$

- ▶ reflection moveout

$$V_{\text{nmo}} = V_{P0} \sqrt{1 + 2\delta}$$

$$\eta = \frac{\epsilon - \delta}{1 + 2\delta}$$

Anisotropic wavefield extrapolation

Differential

$$\frac{\partial^2 p}{\partial t^2} = V_{\text{hor}}^2 \frac{\partial^2 p}{\partial x^2} + V_{P0}^2 \frac{\partial^2 q}{\partial z^2}$$

$$\frac{\partial^2 q}{\partial t^2} = V_{\text{nmo}}^2 \frac{\partial^2 p}{\partial x^2} + V_{P0}^2 \frac{\partial^2 q}{\partial z^2}$$

$$\begin{aligned} V_{\text{hor}} &= V_{\text{nmo}} \sqrt{1 + 2\eta} \\ &= V_{P0} \sqrt{1 + 2\varepsilon} \end{aligned}$$

(Fletcher et al., 2009)

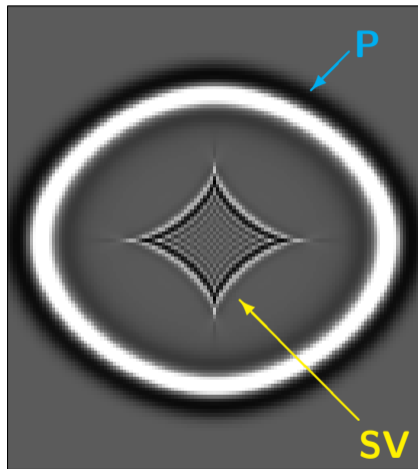
Integral

$$U(\mathbf{x}, t \pm \Delta t) = \int \hat{U}(\mathbf{k}, t) e^{\pm i\phi(\mathbf{x}, \mathbf{k}, \Delta t)} d\mathbf{k}$$

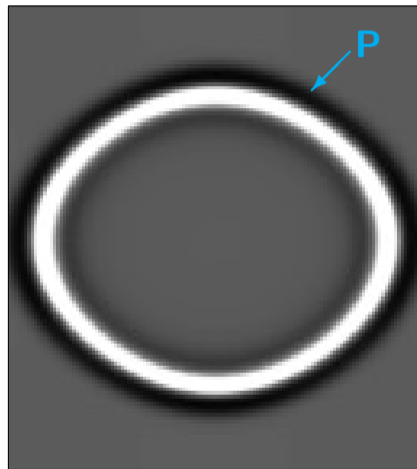
(Fowler and Lapilli, 2012)

(Fomel et al., 2013)

VTI medium with $\eta > 0$

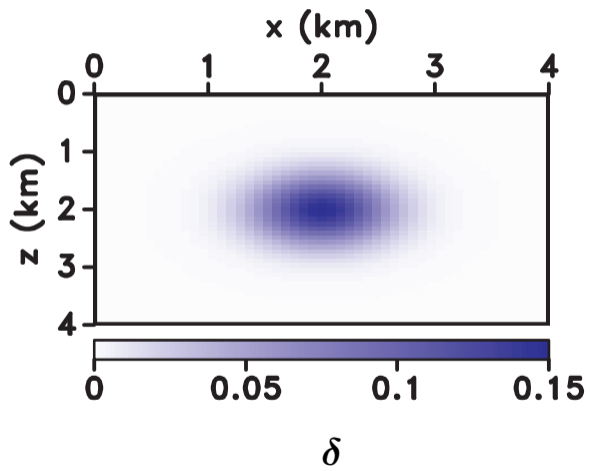
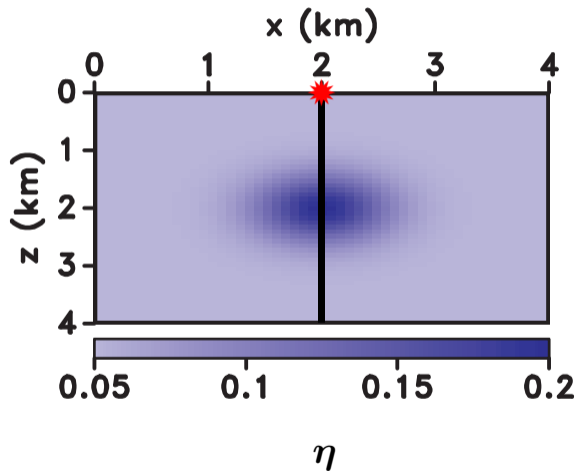


Differential

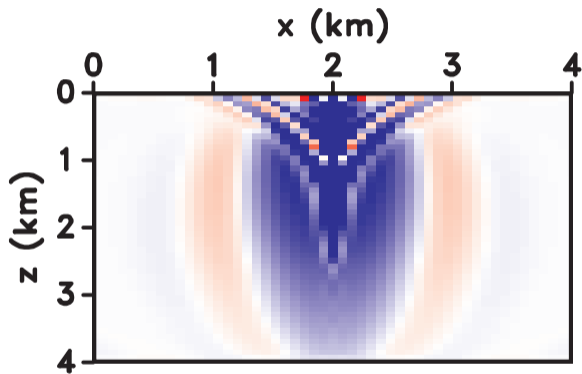


Integral

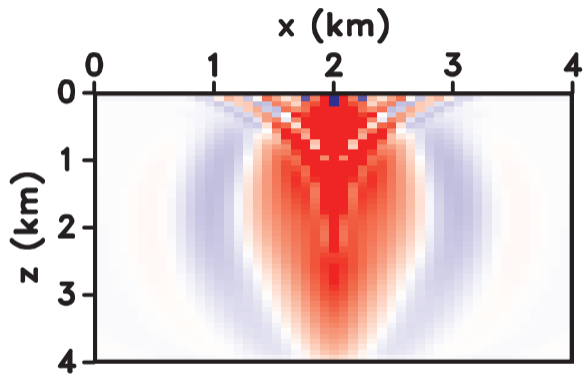
Model with $\eta > 0$



δ -gradients with differential operator

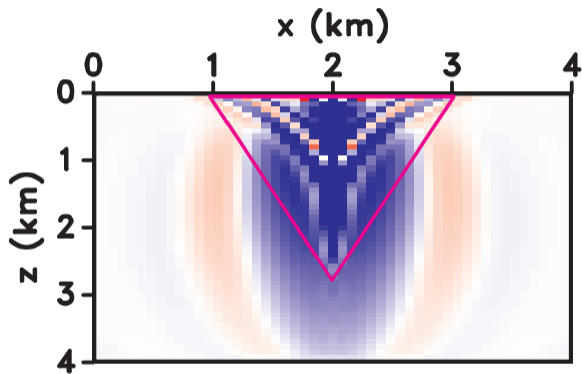


lower

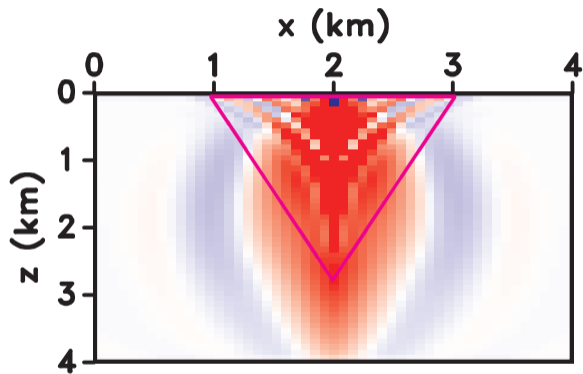


higher

δ -gradients with differential operator

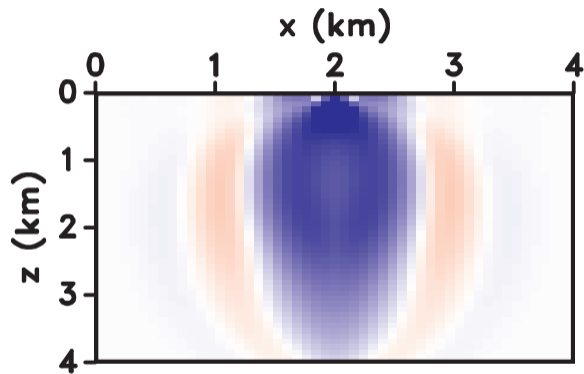


lower

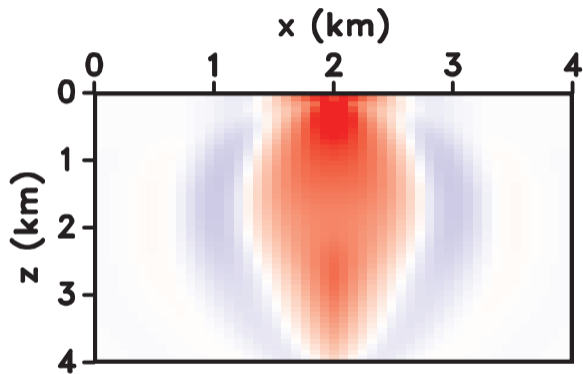


higher

δ -gradients with integral operator



lower



higher

Objective function

$$\mathcal{J} = \mathcal{J}_{\text{refl}} + \alpha \mathcal{J}_{\text{vsp}}$$

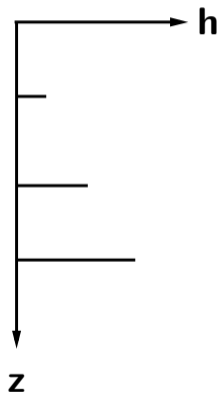
$\mathcal{J}_{\text{refl}}$ - image-domain term

\mathcal{J}_{vsp} - data-domain term

α - weighting coefficient

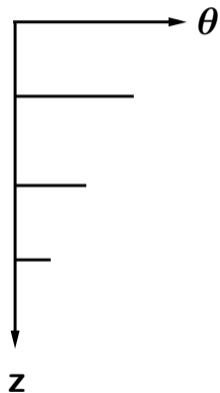
Image-domain criteria

surface-offset CIGs



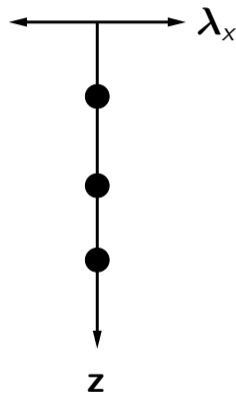
flatness

angle-domain CIGs



flatness

extended CIGs

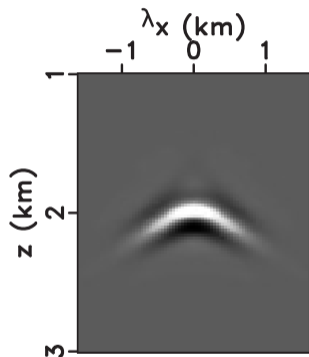


focusing at zero lag

Extended-domain objective function term

$$\mathcal{J}_{\text{refl}} = \frac{1}{2} \|\mathbf{P}(\boldsymbol{\lambda}) \mathbf{I}(\mathbf{x}, \boldsymbol{\lambda})\|^2$$

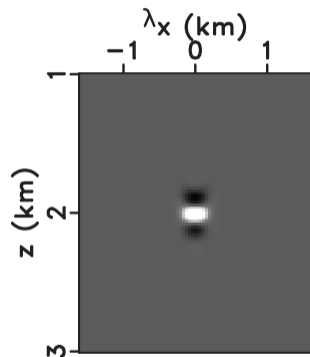
Extended-domain objective function term



Inaccurate

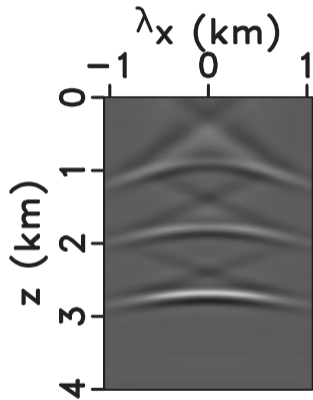
$$\mathcal{J}_{\text{refl}} = \frac{1}{2} \|\mathbf{P}(\boldsymbol{\lambda}) \mathbf{I}(\mathbf{x}, \boldsymbol{\lambda})\|^2$$

→
model update

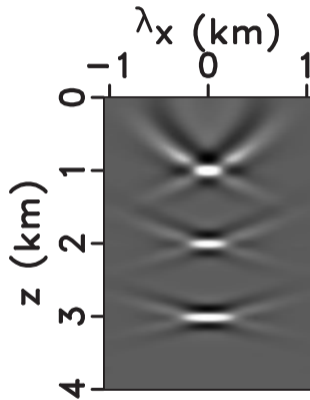


Accurate

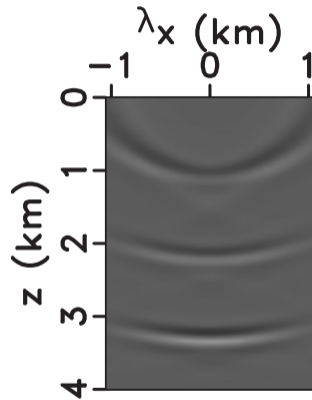
Extended images



lower

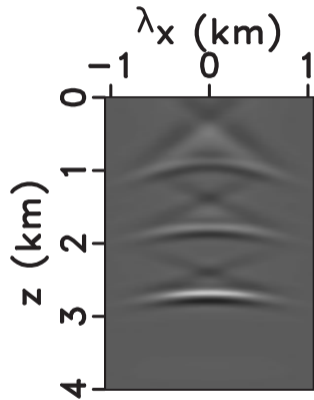


accurate

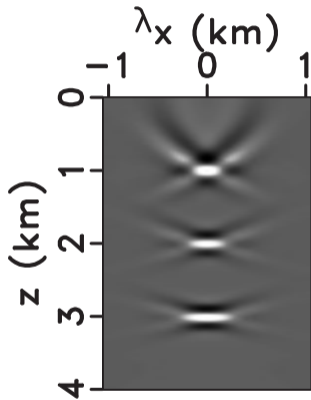


higher

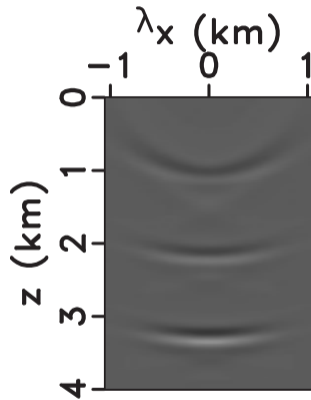
Extended images with partial image-power operator



lower

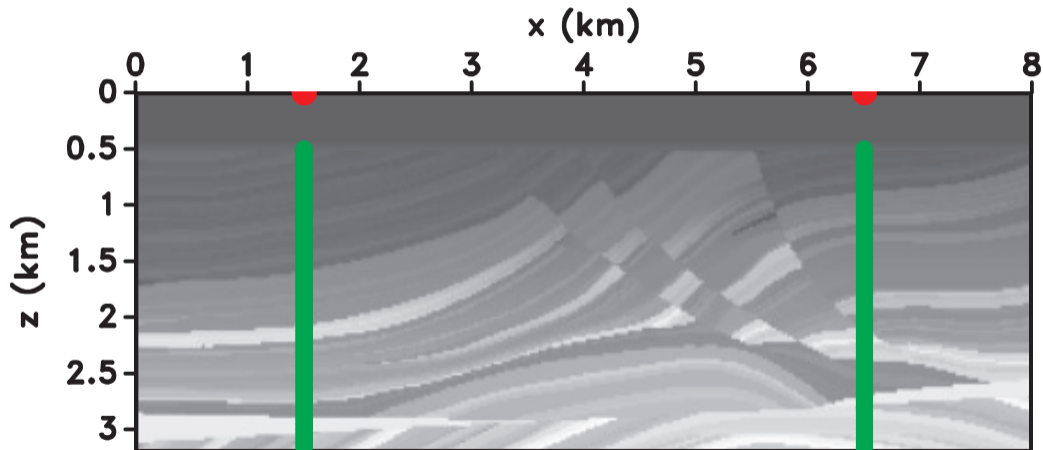


accurate



higher

Marmousi model with two boreholes

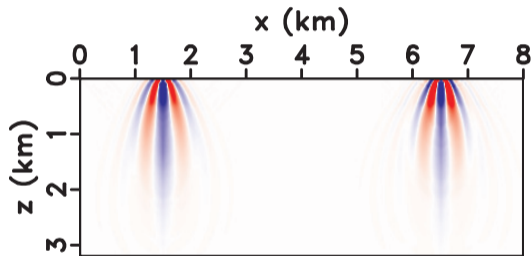


Data-domain objective function term

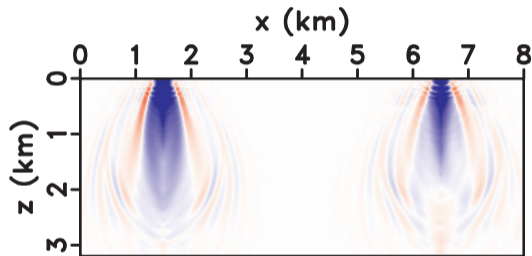
$$\mathcal{J}_{\text{vsp}} = - \sum_{e, x, \tau} \mathcal{W}(\tau) \mathcal{C}(d_{\text{obs}}, u, \tau)$$

(Wu and Alkhalifah, 2017)

Check-shot V_{P0} -gradient

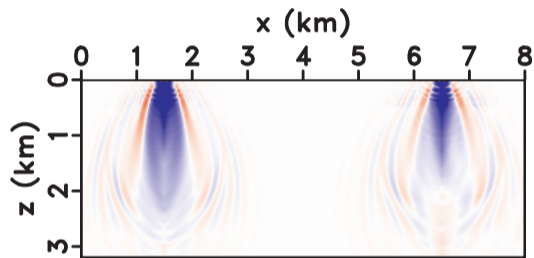


Data-difference



Correlation

Inversion gradient



Initial

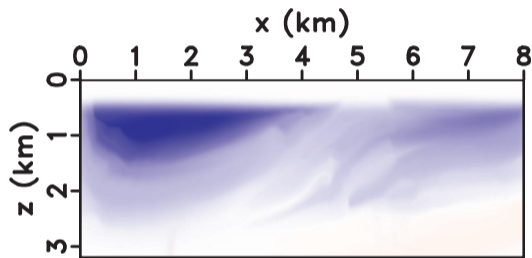
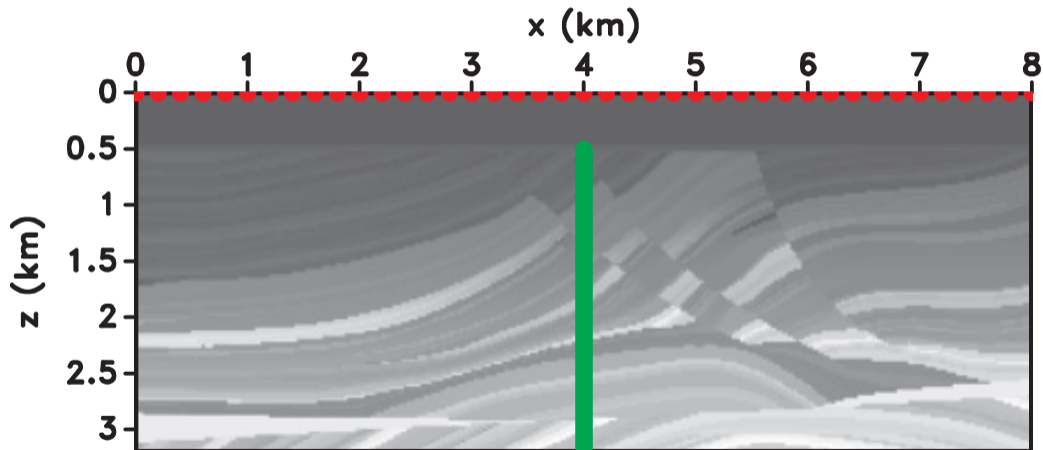
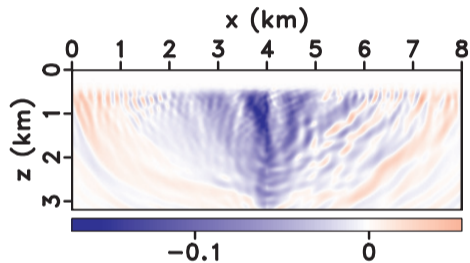


Image-guided

Walkaway VSP geometry



Walkaway VSP V_{P0} -gradient



Initial

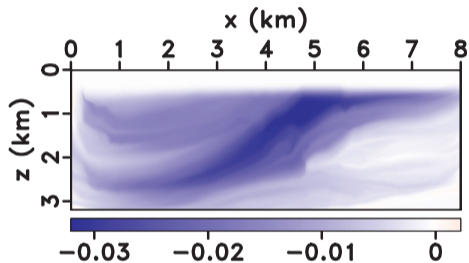
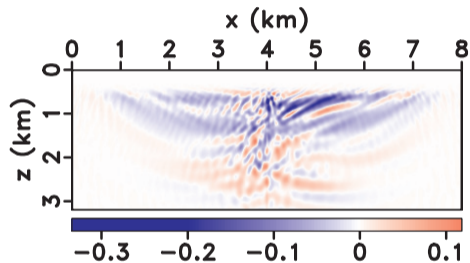


Image-guided

Walkaway VSP η -gradient



Initial

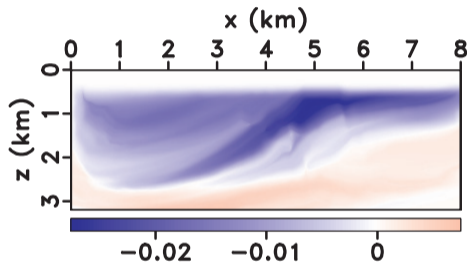
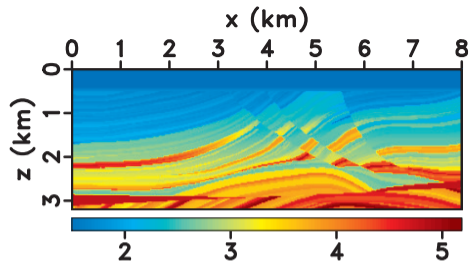
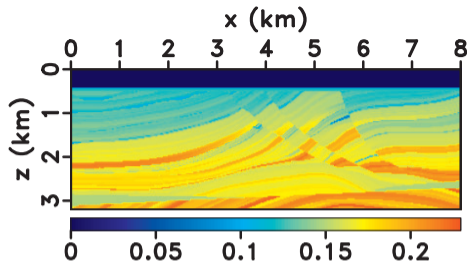


Image-guided

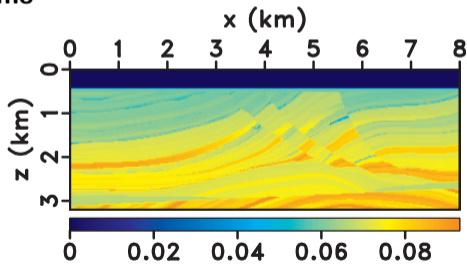
Inversion for Marmousi model



V_{nmo}

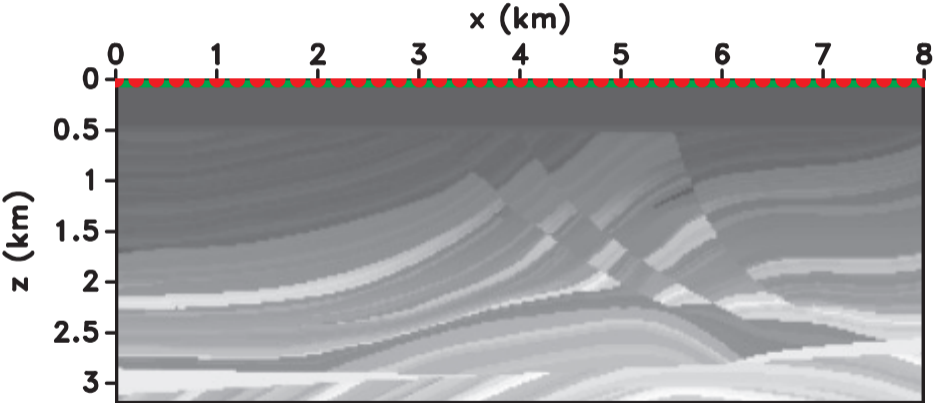


η

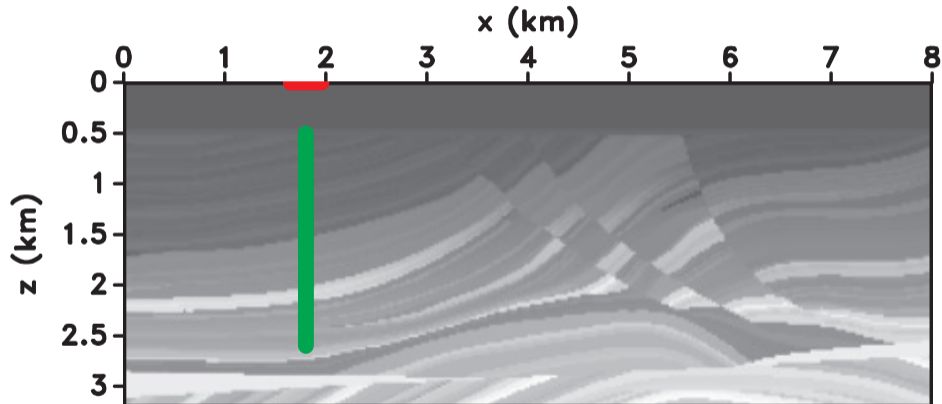


δ

Surface acquisition



Borehole acquisition



Initial V_{nmo} ($\eta = \delta = 0$)

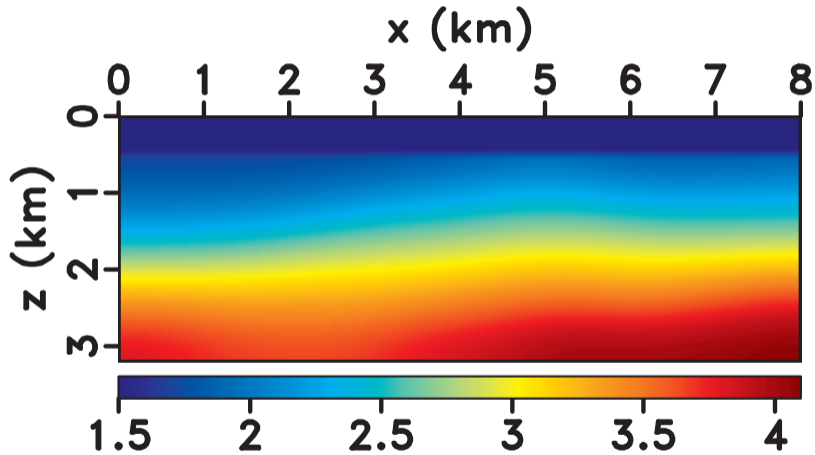
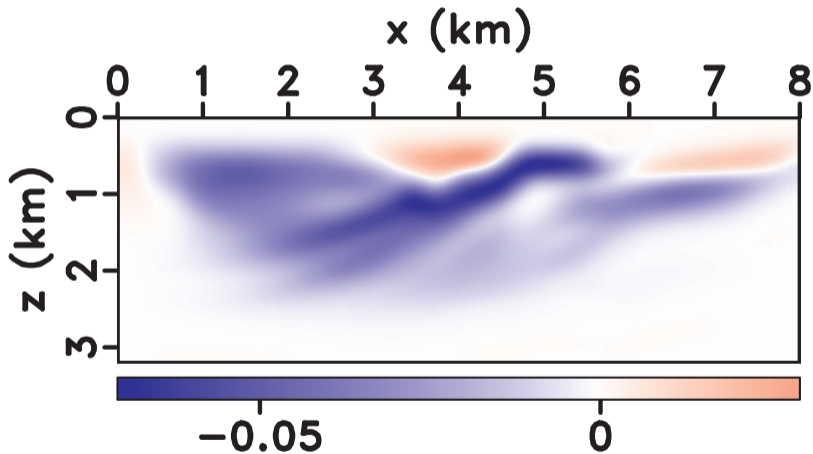
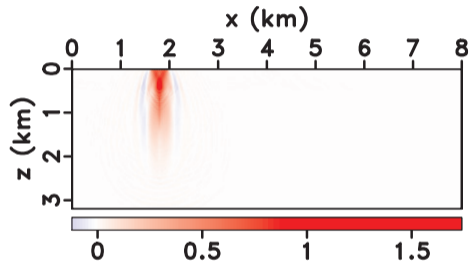


Image-domain gradient $(V_{\text{nmo}}^2, 2V_{\text{nmo}}^2 \eta, V_{\text{P0}}^2)$



Check-shot V_{P0}^2 -gradient



Initial

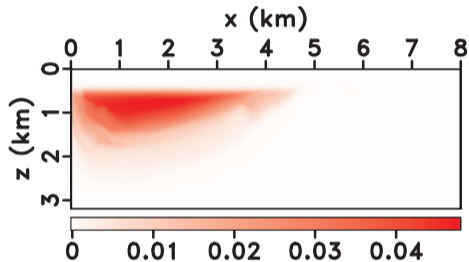
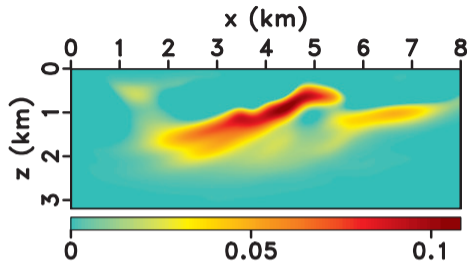
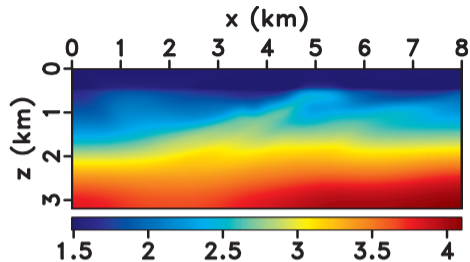


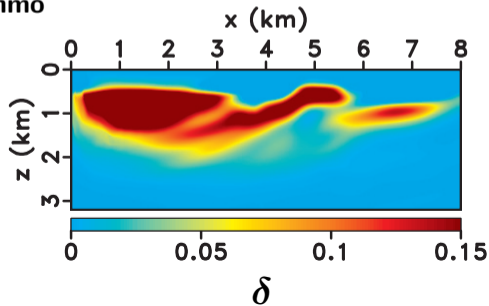
Image-guided

Updated model

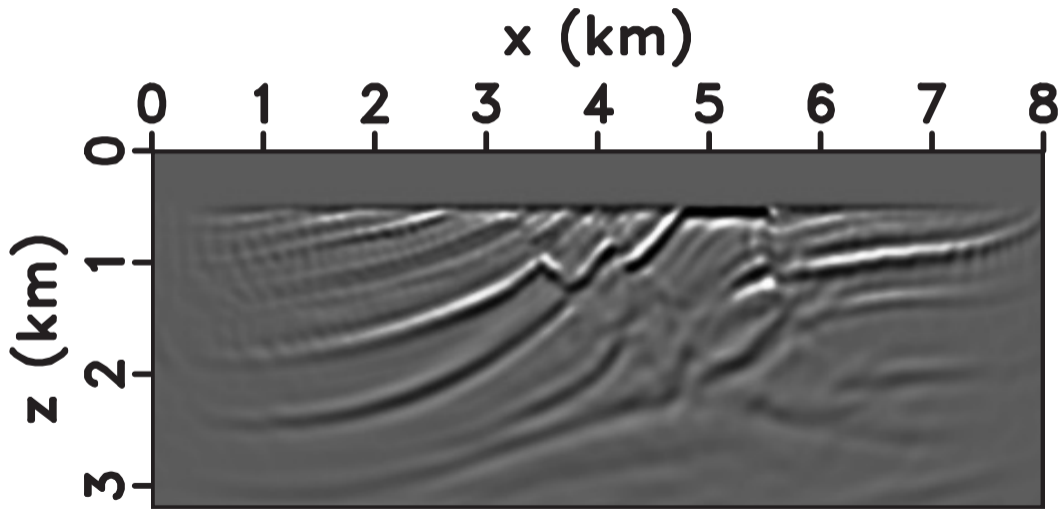


V_{nmo}

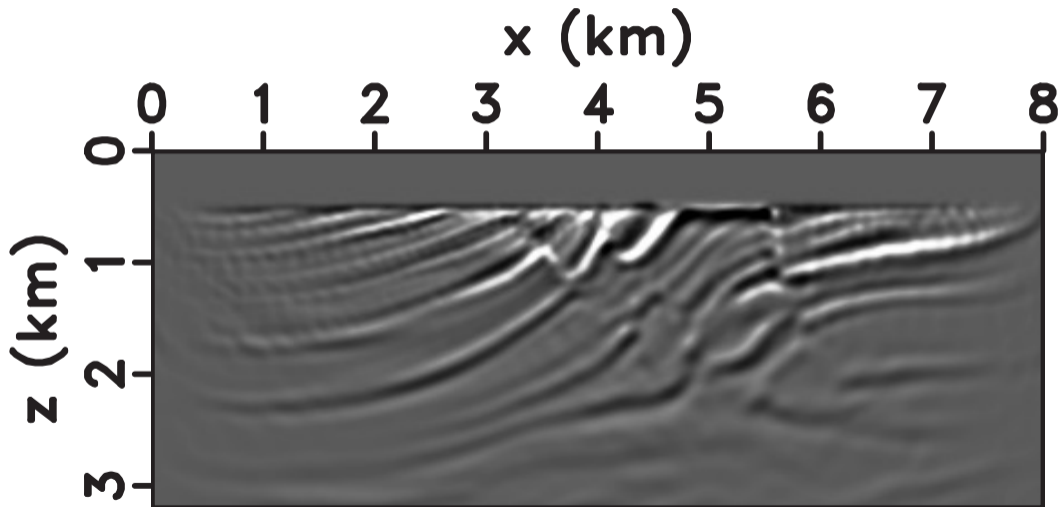
η



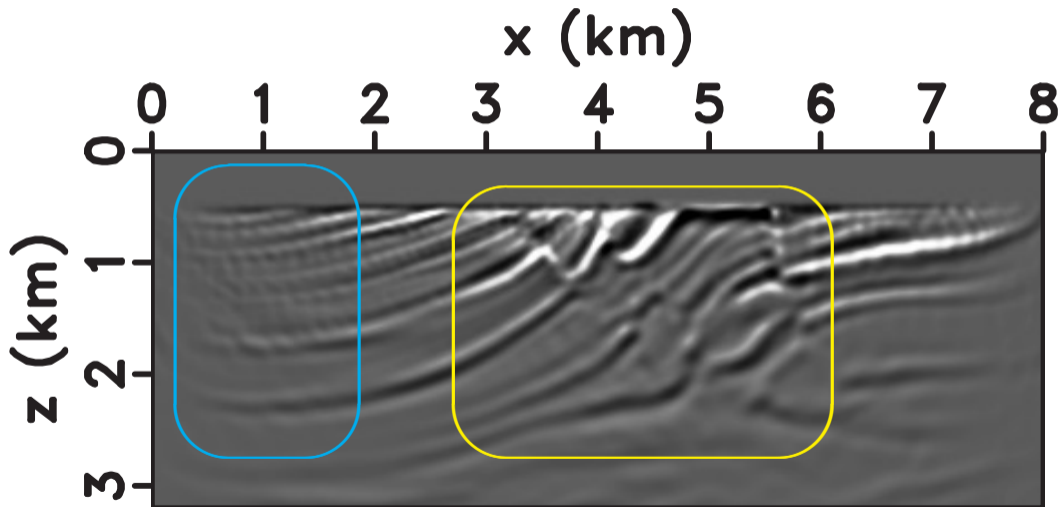
RTM image with initial model



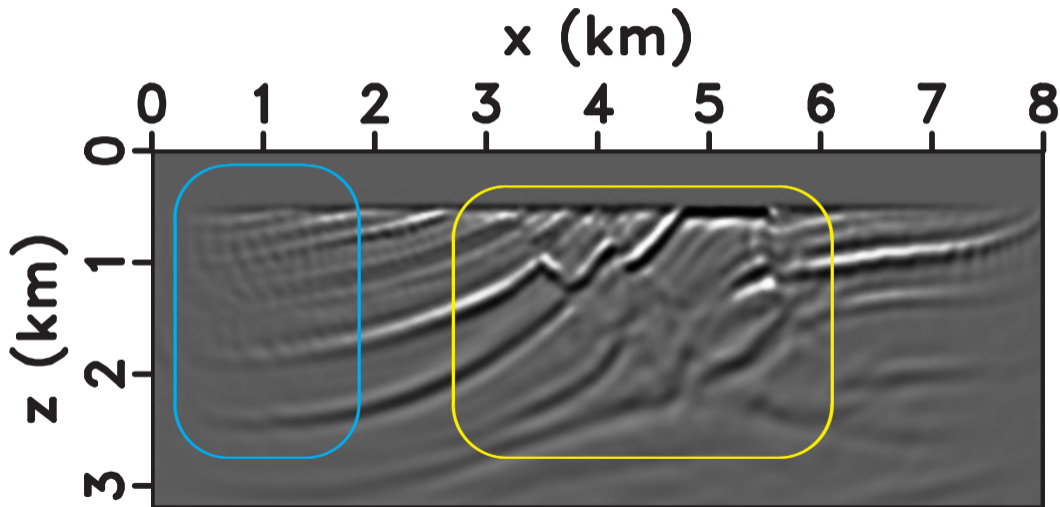
RTM image with updated model



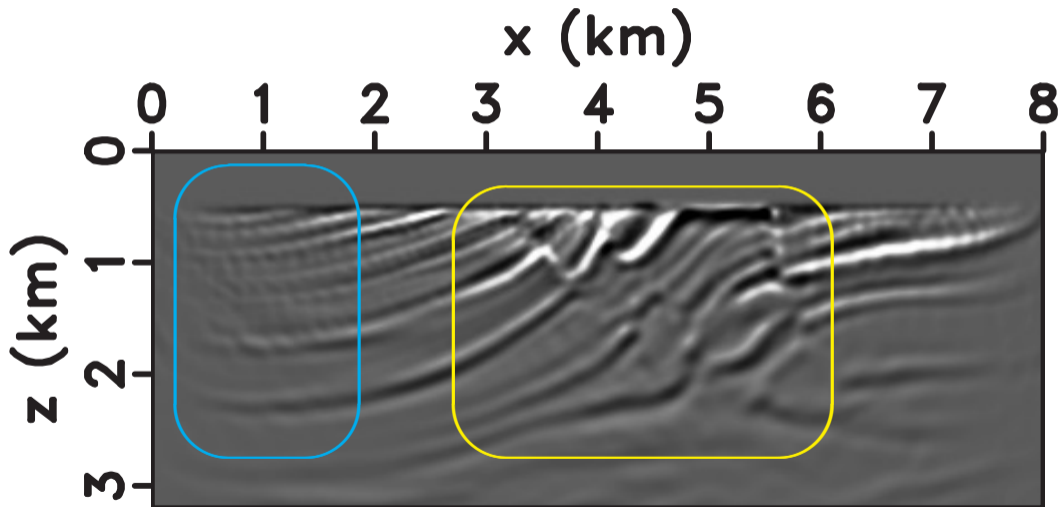
RTM image with updated model



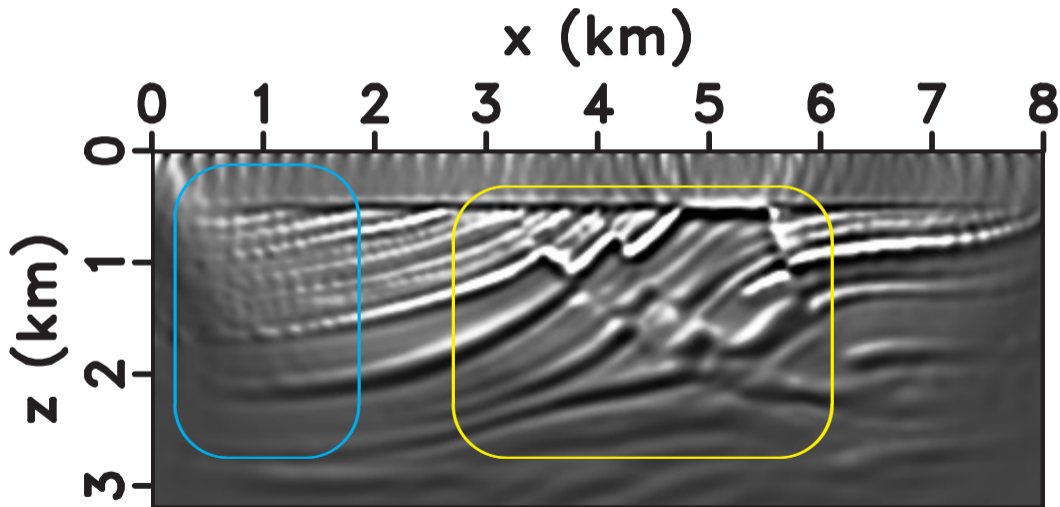
RTM image with initial model



RTM image with updated model



RTM image with accurate model



Summary

- ▶ joint inversion of surface and VSP data
- ▶ image domain: partial image-power
- ▶ data domain: envelope correlation
- ▶ image-guided smoothing
- ▶ inversion for VTI Marmousi model

Future work

- ▶ image preconditioning
- ▶ multi-stage inversion strategy
- ▶ extension to TTI media
- ▶ field-data applications

Acknowledgments

- ▶ Paul Fowler
- ▶ Xinming Wu
- ▶ A-Team